Origin of the ubiquitous fast solar wind

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The solar wind is a direct manifestation of the coronal heating processes which continue to elude us. For over three decades, observations in interplanetary space have identified two types of wind: a slow component with highly variable physical properties also characterized by speeds typically below 500 km/s, and a much less variable fast wind flowing on average at 750 km/s[1]. Connecting these two types of winds to their origins at the Sun is still not resolved. The prevailing view is that the fast solar wind originates from polar coronal holes, and occasionally from coronal holes at low latitudes[2]. That the fast wind reaches the ecliptic plane has been attributed to the faster than radial expansion of their boundaries which are believed to be defined by the neighboring streamers. The recent completion of the pole to pole passage by Ulysses out of the ecliptic between 1992 and 1995 offered an intriguing new finding: namely the predominance of fast solar wind down to at least 40° in latitude, despite the vastly varying aspect of the corona throughout that time interval, and the changes in the so-called boundaries of coronal holes[3]. Using observations from the Ultraviolet Coronagraph Spectrometer (UVCS) on SOH0[4], we provide here the first direct measurements showing how the fast solar wind extends to within less than 20° of the axes of streamers, and that these axes are the sole source of

the slow solar wind. The UVCS observations also provide direct evidence that the fast solar wind flows along radially directed field lines pervading coronal holes and the quiet sun.

Significant advances in our understanding of the origins of the slow and fast solar wind have come from the morphology of solar wind velocity, density fluctuation and density deduced from radio occultation measurements of the corona. Large-scale gradients in velocity indicated that the slow wind emanated from localized sources in the corona overlying the streamer belt[5]. That the slowest wind coincided with conspicuously high levels of density fluctuating characteristic of coronal streamer stalks[7], provided the first observational evidence that streamer stalks were the sources of the slow solar wind. By comparing ranging measurements of path-integrated density with simultaneous white light observations, Woo and Habbal[8] found that structures in the low corona extended radially outwards into interplanetary space. The radio observations thus strongly suggested that the corona was dominated by radially expanding raylike structures originating from polar coronal holes as well as the quiet Sun. Low levels of density fluctuation that are characteristic of the fast wind[5,9–10] were common to both coronal hole and quiet Sun regions. These results, taken together with the predominance of the fast solar wind found by Ulysses during its polar passages[3], led these authors to conclude that the fast solar wind must originate not only from polar coronal holes but also from the quiet Sun, and that it propagates along the raylike structures.

With the advent of SOHO, UVCS has proven to be an unprecedented tool for probing the physical conditions in the inner corona[1]1. One of the unique advantages of this instrument is the measurement of coronal spectral lines formed primarily by the resonance scattering of ions in the corona of the corresponding lines emitted from the solar disk. These measurements extend to at least 3.5 R_s in coronal holes, and to 10 R_s in denser coronal plasmas[4]11. The strongest of these lines are the Ly α 1216 Å and the O VI 1032 and 1037.6 Å lines. One of the interesting properties of the oxygen lines (and other minor ion lines observed by this instrument) is that collisional excitation also contributes to the formation of the line. However, as the ions start to flow outwards in the corona, the fraction of the spectral line formed by resonance scattering becomes Doppler-shifted out of resonance with the disk emission[12-14]. Subsequently, the relative ratio between these two lines changes drastically. Known as Doppler-dimming, this effect influences the two lines differently because of the additional pumping of the 1037.6 Å line by the disk emission of the C II line at 1037 Å . Hence the ratio of the intensity of the two oxygen lines yields a direct measure of the outflow velocity of these ions, which could be different from the proton/electron velocity. A ratio of 2 occurs for a flow speed of 94 km/s. A minimum in the ratio occurs for a flow speed of 188 km/s when the C II line in turn becomes Doppler-shifted out of resonance[14]. The Doppler dimming and pumping effect has been demonstrated successfully with UVCS in a number of coronal hole observations[11].

Taking advantage of the powerful diagnostic tool offered by the ratio of the oxygen lines, as well as the contrasting signatures of the fast and slow solar wind in Doppler scintillation measurements, coordinated radio occultation and UVCS observations were carried out for the first time during the Galileo solar conjunction between January 17 and 20, 1997. In addition, a second set of observations was made by UVCS alone on April 23, 25 and 27, 1997, to map the corona around a well-isolated streamer. While a number of UVCS observations of streamers have been made[16], the perspective and interpretation of the present observations is new.

Figure 1 shows images of the corona taken with the white light coronagraph (LASCO)[15] on SOHO on one day during each of these observing periods. The slit positions of the UVCS detector were chosen to coincide with the passage of the radio signal from Galileo through the corona starting on January 17 (Figure la). The south polar coronal hole measurements on January 19, were made by UVCS alone when Galileo was occulted by the Sun. The measurements off the west limb followed Galileo on the egress. To map the solar wind velocity over a larger area of the corona, UVCS measurements taken on April 23, 25, and 27 (Figure lb), were centered on the axis of a well-isolated streamer on the west limb, as well as at 20° and 40° north of that position.

Slit positions off the axes of the streamers in both data sets offered the first direct evidence for the sharp transition in flow speed from the axis of the streamer to the ambient corona. A typical example illustrating this transition is shown in Figure 2 for the UVCS observations of April 27 (see Figure lb) at 3.5 R_s at 20° north of the streamer axis at 267°. This figure illustrates very vividly how the relative height and intensity of the two oxygen line profiles change significantly as a function of position angle or latitude away from the streamer axis or stalk. By measuring the intensity of the two lines and their ratio along the slits for different heliocentric distances (Figure 3), contours of the intensity ratio equal 2 (or equivalently a ion flow speed of 94 km/s) for the two observation sets were obtained (Figure 1). Most striking in these contours is the very sharp latitudinal gradient in wind speed that occurs very close to the axis of the streamers. Not only is the change in ratio indicative of changes in solar wind character, but so is the width of the spectral lines (Figure 2). The lower ratio and broader profile are typical of a fast and hot wind (as far as the oxygen ions are concerned) comparable to UVCS measurements in polar coronal holes[11]. This combination is also a strong indication of the anisotropy of the velocity distribution in the fast wind as shown in [11]. Since the line ratios are derived from measurements along the line of sight, the flow speed is high over a large fraction of the line of sight. Along the axis of the streamer, on the other hand, the ratio is higher, and the lines narrower, as also reported in earlier UVCS observations of streamers[16].

The corresponding radio occultation measurements by Galileo were characterized by low levels of Doppler scintillation consistent with those observed outside a streamer stalk[7], and typical of fast wind. They, therefore, provide a direct confirmation that the UVCS measurements, at the location of the Galileo radio measurements, are typical of fast solar wind, as evidenced by the contour in Figure la. This result also confirms that low levels of Doppler scintillation are a proxy for the fast wind,

The contours outlining the transition from fast toslow wind are clearly aligned with or cross the radially extending raylike structures prevailing in the corona (Figures la-b), There is no evidence forany diverging field lines, and no distinction in morphology between the extension of the rays from polar to low latitude regions. These observations thus confirm the view recently proposed by Woo and Habbal[8] that the fast solar wind does not originate primarily from polar coronal holes, but that its ubiquitous nature, so vividly evident in the Ulysses measurements[3], derives from its origin in the quiet Sun too. This new view also provides a natural explanation for the absence of significant latitudinal gradient in the magnetic field observed by Ulysses at high latitudes'.

That there exist two types of solar wind with different physical characteristics can be readily understood if we consider their corresponding magnetic sources. It is very plausible that the radially extending raylike structures originate within the boundaries of supergranular cells which indiscriminately cover the solar surface. These cells are preserved in coronal holes because of the absence of large scale closed magnetic field lines. In the quiet Sun, the supergranular cells at coronal heights are essentially preserved except for occasional disruptions by large scale magnetic field lines interconnecting widely separated magnetic regions. The axes of the streamers, which carry the slow solar wind, on the other hand, belong to the large scale coronal structures that have dominated our impression of the corona for so long and which derive from deep-rooted multipolar fields. The new clues provided by the results of this study should lead to new perspectives in the search for the elusive coronal heating mechanisms of the solar wind.

Figure Captions

Figure 1. White Light images of the corona taken with the LASCO C2 coronagraph[15] on SOHO on (a) 17 January (Jupiter as the bright object in the east below the equator, indicating the approximate location of Galileo) and (b) 27 April, 1997. The field of view spans 2 to 6 R_s. The spatial length of the field of view defined by the slit of the UVCS detector is approximately 2 R_s. The slit positions, for observations on January 17 to 20, and April 23, 25 and 27, are shown as vertical lines. They are perpendicular to the radial direction at position angles PA = 97°, 180° and 247° in (a), measured counter clockwise from heliographic north. In (b) PA = 267° coincided with the axis of the streamer. Additional observations were made at 20° and 40° north of that position. The contours in (a) and (b) mark the ratio of the oxygen 1032/1037 line intensities equal to 2, or, equivalently 94 km/s. This ratio increases towards the axis of the streamer, and decreases away from it (see details in Figure 3).

Figure 2. Top: False-color image of the intensity of the O VI 1032, 1037.6 Å and Ly β lines along the slit at $3.5\,R_s$, 20° north of the streamer axis in Figure lb. The horizontal axis is the spectral direction, and the vertical axis represents the spatial direction. The spectral resolution is 0.28 Å per bin. Because of the roll angle of UVCS, north faces down. Bottom: (a), (b) and (c) are the profiles of the two oxygen lines integrated over 4.5', 5.25' and 11.5' fields of view, respectively as indicated by the space between the arrows in the image above. The ratio of the line intensities is (a) 2.1 $\pm$ 0.1, (b) 1.7 $\pm$ 0.25 and (c) 1.4 $\pm$ 0.5 respectively.

Figure 3. Plots of the ratio of the two oxygen lines versus heliocentric distance R/R_s for different position angles PA = O, $\pm$ 10 and $\pm$ 20° measured north (+) or south (-) with respect to the axis of the streamers (top three panels: January east limb observations, lower four panels: April observations). For small heliocentric distances the data were binned over 2-4'. At distances larger than 3.5 R_s the data were binned over

11' (corresponding to an uncertainty of 2°) when the streamer axis was not in the field of view. It is clear from these plots that the wind reaches a speed of 94 km/s (or ratio = *2)* around 4.5 R_s along the axes of streamers (PA = O°). In contrast, the wind is faster closer to the Sun as it moves away from the axis of the streamers, for example, at 3.5 - 4 R_s for PA = $\pm 10°$, or 2.5-3 R_s for PA = $\pm 20°$. The first minima seen at $\pm 20°$ are very close in heliocentric distances to those found in coronal holes[11], and correspond to 188 km/s. An uncertainty of 0.5 in the ratio corresponds to an uncertainty of 25 km/s in speed.

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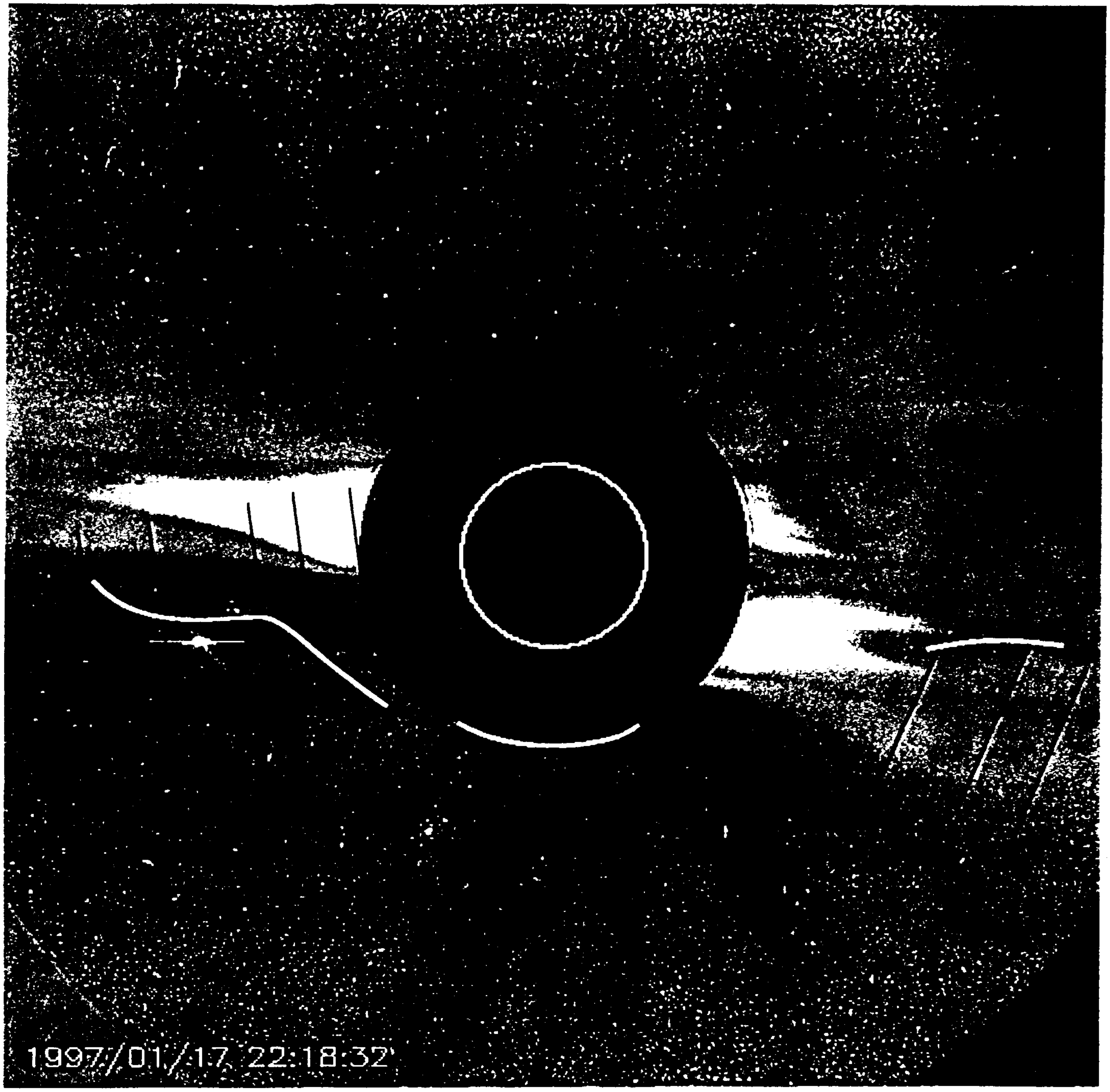
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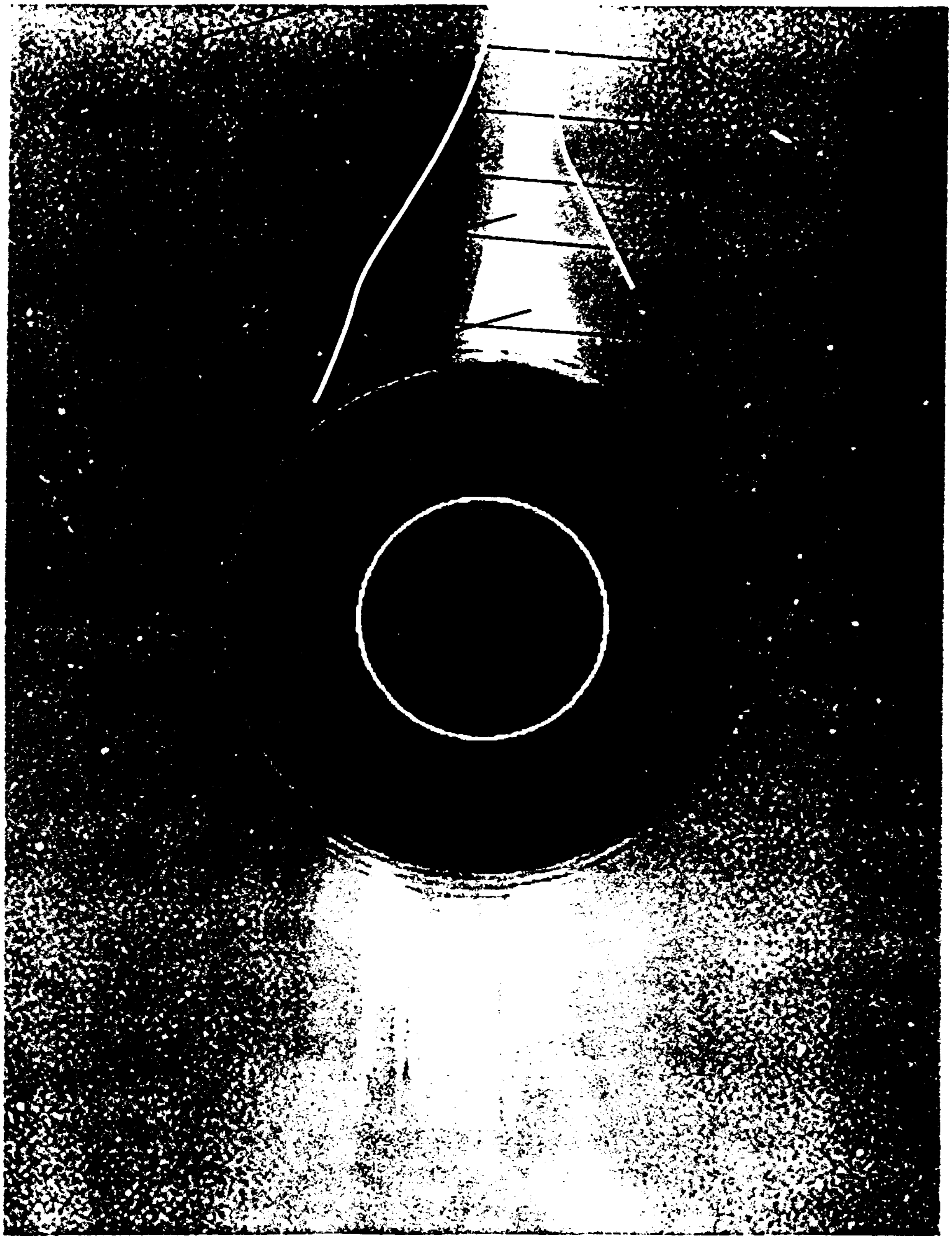

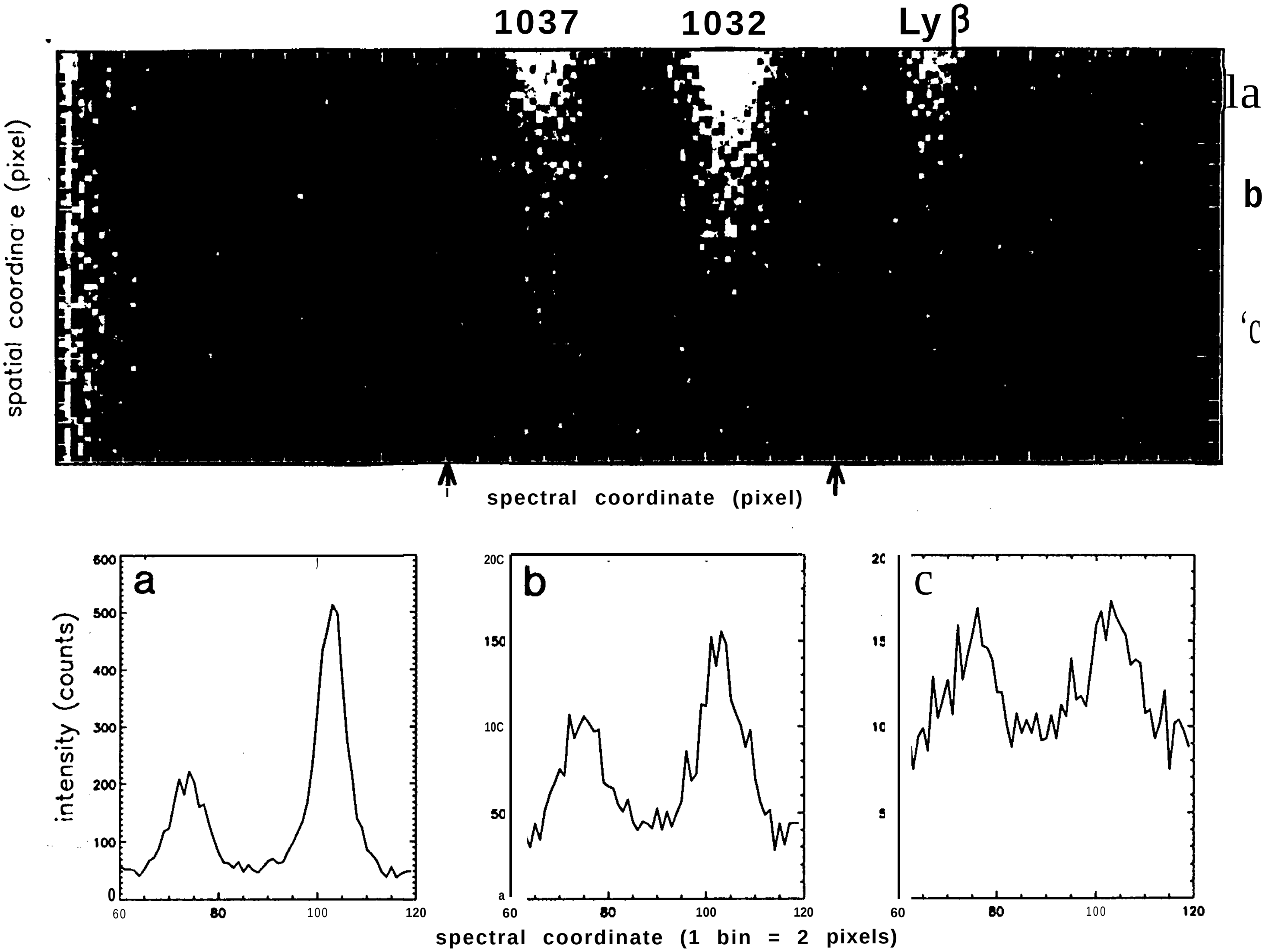

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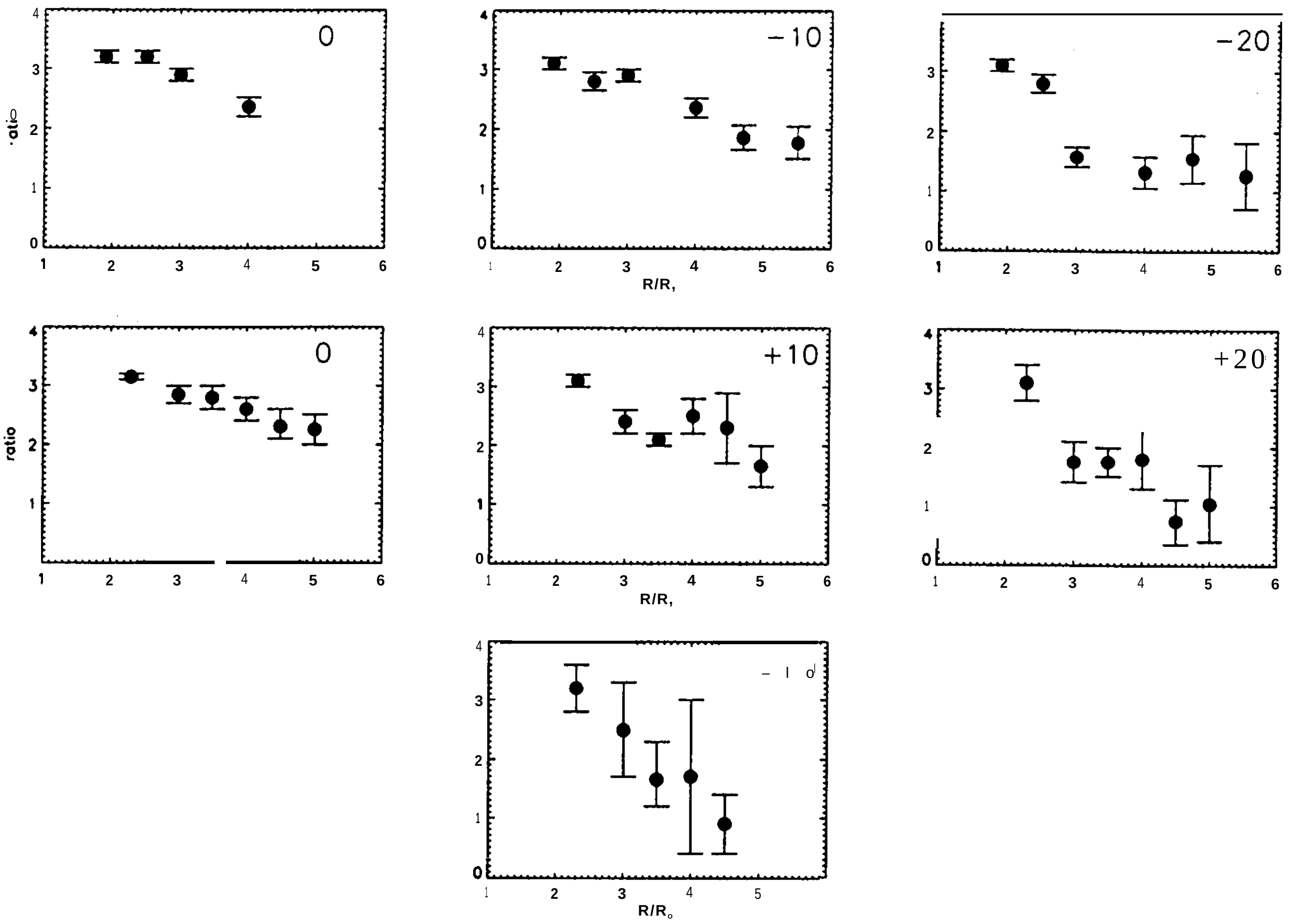
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